Design and Test Results of a 600-kW Tetrode Amplifier for the Superconducting Super Collider*

Daniel E. Rees and Donna L. Brittain
Los Alamos National Laboratory
P.O. Box 1663, Los Alamos, NM 87545

James M. Grippe and Orlando Marrufo
Superconducting Super Collider Laboratory
2550 Beckleymeade Ave., Dallas, TX 75237

Abstract

This paper describes the design and testing of a pulsed 600-kW tetrode amplifier that will be used to drive a radio-frequency quadrupole (RFQ) for the Superconducting Super Collider (SSC). Three stages of amplification provide a nominal gain of 77 dB and peak output power of 600 kW. The amplifier is operated at a pulse width of 100 µs and a repetition frequency of 10 Hz. This paper presents the RF design and calculated operating conditions for the amplifier. Details of the electrical design are presented, along with test results.

I. INTRODUCTION

The purpose of the radio-frequency quadrupole (RFQ) amplifier is to provide an adequate amount of power at the proper operating frequency to enable the RFQ to increase the velocity of the input beam from .00864 times the speed of light to .0729 times the speed of light. The energy in the beam increases from 35 keV to 2.5 MeV. To perform this function the amplifier must provide a minimum of 225 kW at a frequency of 427.617 MHz at each of two input ports of the RFQ. In addition, enough overdrive must be available to ensure a fast fill time. To adequately meet the requirements, the amplifier must meet the performance requirements specified in Table 1.

Table 1
600-kW Amplifier Electrical Requirements

Operating Frequency	427.617 MHz
Bandwidth	300 kHz (minimum)
Power Output	600 kW (peak)
Gain	77 dB (nominal)
Pulse Length	100 µs
Pulse Repetition Rate	1 to 10 Hz
Pulse Droop	1% (maximum)
Input VSWR	1.5:1 (maximum)
Linear Range	15% to 85% of peak power rating
Amplitude Stability	<0.5 dB within any one hour
Phase Stability	<10 deg. within any one hour
Spurious Signals	>60 dB below carrier
Prime Power	208 VAC, 3 phase

A similar amplifier with slightly different performance characteristics—300-kW, 425-MHz, 2% duty factor—was developed for the Ground Test Accelerator (GTA). This GTA amplifier was modified to meet the Superconducting Super Collider (SSC) requirements.

The SSC amplifier is located in the source area of the LINAC Building. Cooling water, whose temperature cannot exceed 95°C, is provided for cooling the output cavity. Building temperature is well regulated. Therefore, no special provisions are necessary for air cooling, other than fans and blowers.

Input RF is obtained from the low-level RF control system, which is designed to maintain cavity field amplitude and phase to a preset level in the presence of beam-induced field perturbations. A high-power circulator isolates the load from the amplifier. The load on the amplifier can be manually switched between the accelerating cavity or a test load via a coaxial switch.

II. OPERATING CONDITIONS AND AMPLIFIER CONFIGURATION

The SSC amplifier is a three-amplifier chain, consisting of an 800-W solid-state driver, an intermediate triode amplifier, and a final tetrode amplifier.

The solid-state amplifier requires a maximum input of 13 dBm and can provide up to 800 W of power for 2-ms pulses at a maximum repetition rate of 10 Hz. The amplifier has a 4% bandwidth, and its output is protected by an internal circulator. It is configured to accept an optical trigger, which is used in conjunction with a PIN diode switch to act as an RF gate.

The intermediate amplifier uses an EIMAC 8938 triode. It is configured to be cathode-modulated with a grounded grid. A high-power hexfet is driven into saturation to modulate the cathode. The triode is operated at its rated dc voltage of 4 kV by means of a 5-kV power supply that charges a small capacitor bank to provide the pulsed current.

*This work supported by the U.S. Department of Energy.

Approximately 50 ohms of series resistance is inserted between the capacitor and triode to dissipate the energy in case of an internal tube arc.

The final amplifier is a Burle 4616 tetrode. It requires approximately 500 W of filament power. The operating conditions for the cathode, as well as pertinent maximum operating conditions, are shown in Table 2. The final amplifier requires three high-voltage power supplies. The 25-kV plate voltage is supplied by a 30-kV supply with an average current capability of 80 mA. This supply has a crowbar and small capacitor bank sized to meet the 1% pulse droop requirement. A 3-kV screen supply and 1-kV grid supply are also required. The screen supply feeds a small capacitor bank to supply the pulsed screen current. The screen supply does not use a crowbar triggered simultaneously with the plate supply crowbar. Rather, series resistance is used to limit the current and dissipate the energy that could result from a tube arc.

To provide the required linear range of operation, the solid-state amplifier is operated class AB, the intermediate triode amplifier is operated class A, and the final tetrode amplifier is operate class B. The intermediate triode amplifier takes advantage of the cathode modulator to operate class A during the RF pulse without suffering the corresponding anode dissipation during the interval when the RF pulse is not present.

Table 2
4616 Operating Conditions

Operating Parameter	Value	Max. Value at 100 µs
DC Plate Voltage	25,000 V	25,000 V
DC Screen Voltage	1,800 V	
DC Grid Voltage	-300 V	
DC Plate Current	38.2 A	80 A
DC Screen Current	2.25 A	15 A
DC Grid Current	1.4 A	15 A
DC Cathode Current	42 A	
Fund. Peak Plate Current	64 A	
2nd Harmonic Peak Plate Current	35 A	
3rd Harmonic Peak Plate Current	8 A	
Fund. Peak Cathode Current	71 A	
Peak Plate Swing	20,000 V	
Output Power	638.7 kW	
RF Plate Load	313 Ω	
Peak Grid Swing	460.0 V	
Drive Power	540 W	
RF Grid Input Resistance	148 Ω	
Peak Plate Dissipation	302 kW	
Peak Screen Dissipation	4050 W	
Peak Grid Dissipation	156 W	

III. TEST RESULTS

Test results for the 600-kW amplifier are shown in Figures 1 and 2. Figure 1 shows the frequency response of the amplifier at the upper end of the linear range. Figure 2 shows the linear performance of the amplifier. The test conditions are summarized in Table 3. Table 4 summarizes the test results.

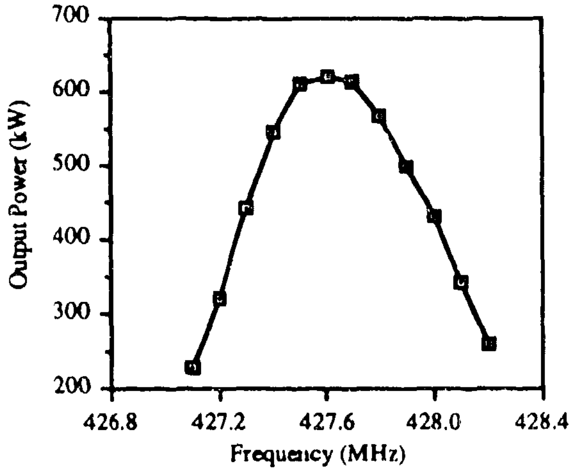

Figure 1. Frequency Response

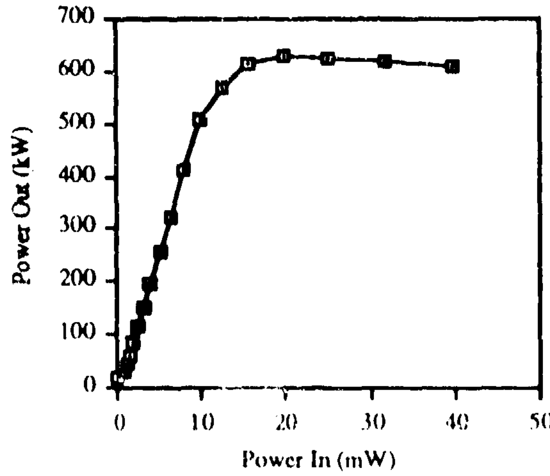

Figure 2. Linear Dynamic Range

Table 3
Test Operating Conditions

Parameter	Value
4616 Grid Voltage	-380 V
4616 Anode Voltage	26,000 V
4616 Screen Voltage	2200 V
4616 Filament Current	510 A

Table 4
Test Results

Parameter	Value
Maximum Power Output	625 kW
Linear Range	200 kW to 500 kW
Gain	77.4 dB (nominal)
3-dB Bandwidth	900 kHz
1-dB Bandwidth	550 kHz
Efficiency	63%

Note: The dc anode voltage used for testing is slightly above the ratings. This was necessary because the high-voltage dc power supply had a series resistance that would drop approximately 1 kV during the RF pulse. We did not suffer any degradation in operational testing as a result of the 26-kV anode voltage, however.

IV. CONCLUSION

We have successfully modified the GTA 300-kW amplifier to operate as a 600-kW amplifier for SSC. The amplifier met or exceeded all performance requirements and is currently in service at SSC.